NASA-CR-205088

OJ/T

RENEWAL PROPOSAL
AND
PROGRESS REPORT #1

ENTITLED

LABORATORY EVALUATION AND APPLICATION OF MICROWAVE ABSORPTION PROPERTIES UNDER SIMULATED CONDITIONS FOR PLANETARY ATMOSPHERES

to the

Planetary Atmospheres Program of the
National Aeronautics and Space Administration
for Grant NAG5-4190

Principal Investigator:
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Georgia Institute of Technology
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Report Period: April 1, 1997 through December 31, 1997

Proposed Renewal Period: January 1, 1998 through December 31, 1998

Submitted: August 1997

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COVER PAGES:

I. INTRODUCTION AND SUMMARY

Radio absorptivity data for planetary atmospheres obtained from spacecraft radio occulation experiments and earth-based radio astronomical observations can be used to infer abundance of microwave absorbing constituents in those atmospheres, as long as reliable information regarding the microwave absorbing properties of potential constituents is available. The use of theoretically-derived microwave absorption properties for such atmospheric constituents, or using laboratory measurements of such properties under environmental conditions which are significantly different than those of the planetary atmosphere being studied, often leads to significant misinterpretation of available opacity data. For example, laboratory measurements completed recently by Kolodner and Steffes (1997, preprint attached as Appendix B) under this grant (NAG5-4190) and under the previous grant (NAGW-533, before January 1, 1997), have shown that the opacity from, H_2SO_4 under simulated Venus conditions is best described by a different formalism than was previously used. The recognition of the need to make such laboratory measurements of simulated planetary atmospheres over a range of temperatures and pressures which correspond to the altitudes probed by both radio occultation experiments and radio astronomical observations, and over a range of frequencies which correspond to those used in both radio occultation experiments and radio astronomical observations, has led to the development of a facility at Georgia Tech which is capable of making such measurements. It has been the goal of this investigation to conduct such measurements and to apply the results to a wide range of planetary observations, both spacecraft and earth-based, in order to determine the identity and abundance profiles of constituents in those planetary atmospheres.

II. PROGRESS REPORT

Since our last Technical Progress Report (Progress Report #22 for the previous grant, NAGW-533), a large amount of research has been completed. Thus, this report highlights all new results obtained since the last report (July 1996).

A. Laboratory Measurements under Simulated Venus Conditions

From 1991 through 1994, we were active in using the Magellan spacecraft to probe the Venus atmosphere by way of radio occultation studies. One key aspect of the Magellan radio occultation results is the high percentage accuracy of the measured profiles of 13 cm and 3.6 cm absorptivity; typically ±10-15%. To take advantage of these new profiles, so as to develop highly accurate abundance profiles of the microwave absorbing constituents, one must know the microwave absorbing and refracting properties of the constituents very accurately. At 13 cm, the opacity immediately below the clouds is almost all due to gaseous sulfuric acid (H_2SO_4). Sulfuric acid is, of course, the predominant constituent in the Venus clouds. Understanding the spatial and temporal variations in its gas-phase abundance gives insight into the dynamical processes which affect cloud formation, as well as into the thermochemical processes which constrain the abundances of other reactive constituents in the Venus atmosphere such as COS, H_2O, CO, SO_2, and SO_3. Over the past grant year, we have completed a laboratory measurement program of the absorption and refraction of gaseous H_2SO_4 in a CO_2 atmosphere under simulated Venus conditions, at selected wavelengths from 1.3 to 13.5 cm (frequencies from 2.2 to 22 GHz). The results of these laboratory measurements, with their application to the interpretation of Magellan and Mariner 10 radio occultation microwave absorptivity profiles, yielding abundance profiles for gaseous H_2SO_4, are given in a paper which has been accepted for publication in ICARUS (Kolodner and Steffes, 1997), which is attached as Appendix B. The laboratory results are being used by our group, and other investigators, in the interpretation of NRAO/VLA microwave emission maps of Venus. (See Section II.B).

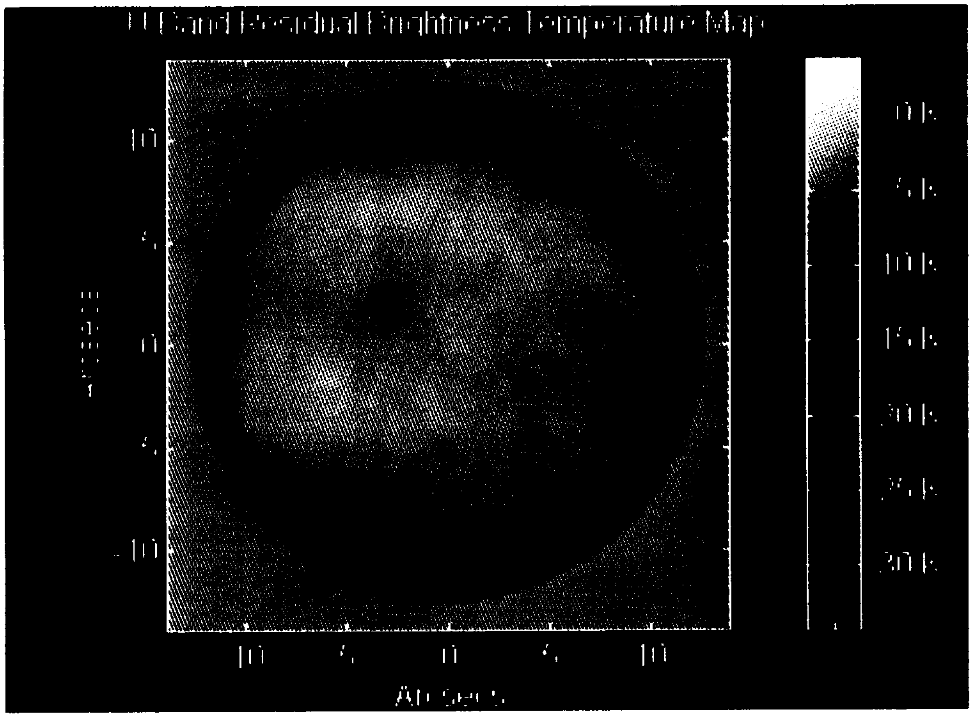
B. Venus Observations and Radiative Transfer Modelling

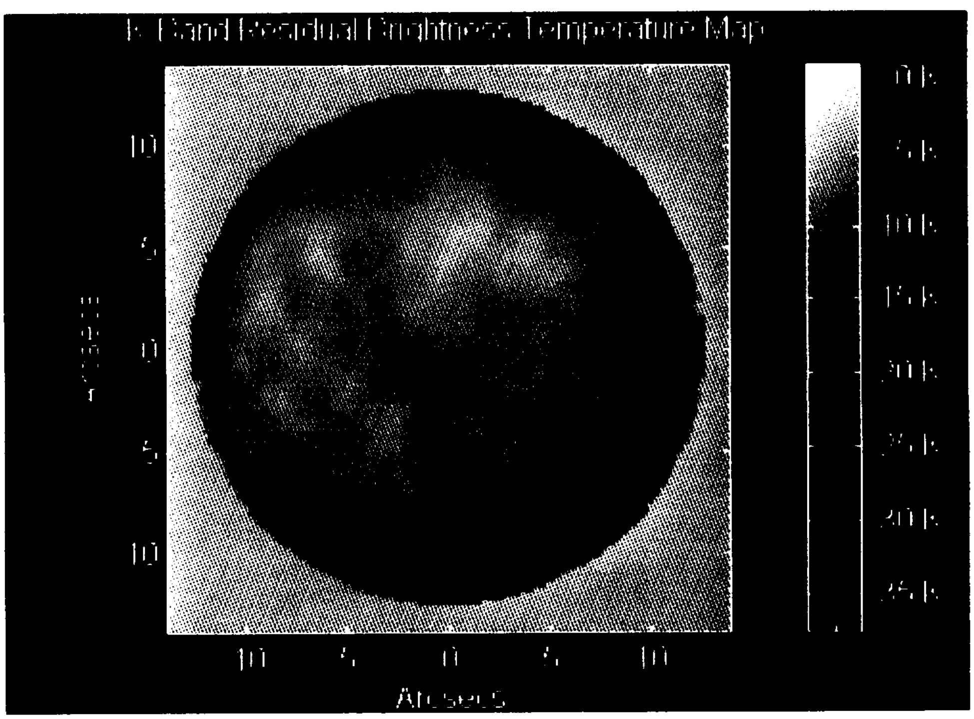
In October 1995, a proposal was submitted to the National Radio Astronomy Observatory (NRAO) for use of the Very Large Array (VLA) for mapping the 1.3 cm and 2 cm emission from Venus. These wavelengths were chosen since they are especially sensitive to the opacity from SO_2 and H_2SO_4. (See Suleiman et al., 1996 and Kolodner and Steffes, 1997.) The observations were conducted on April 5, 1996 by graduate students Shady H. Suleiman and Marc A. Kolodner, assisted by Dr. Brian Butler from NRAO. Initial inspection of the maps derived from these observations (See Figure 1) show darkened regions at latitudes greater than 60 degrees. These darkened regions are larger and more pronounced than simple "limb darkened" zones expected from a uniform disk. They are consistent with the polar darkening observed by the Pioneer Venus Orbiter Infrared Radiometer (OIR) experiment (Taylor, et al., 1980) and ground-based near IR measurements (Hillman, et al., 1996). The interpretation of these emission maps has been conducted using our newly-developed radiative transfer models, which incorporate the new, laboratory-based formalisms for the opacity from SO_2 and gaseous H_2SO_4. The initial results of these interpretive studies will be submitted to Icarus later this year.

C. Other Accomplishments

In October 1996, two (2) conference presentations were made at the 1996 AAS/DPS meeting (Kolodner and Steffes, 1996; Suleiman et al., 1996). A third paper was presented at a special session of the Fall 1996 AGU meeting on the Chemistry of the Lower Atmosphere and Surface of Venus (Kolodner et al., 1996) A fourth presentation regarding interpretation of VLA radio images of Venus was made at the 1997 AAS/DPS meeting (Kolodner et al., 1997). The abstracts for these four Venus-related presentations are attached as Appendix A. One refereed journal paper was also published (DeBoer and Steffes, 1996) and a reprint is attached as Appendix C. Two Ph.D. dissertations were also completed in May 1997 (Kolodner, 1997 and Suleiman, 1997).

Figure 1: a) 2cm-wavelength residual emission from Venus measured with the NASA VLA.





b) 1.3cm-wavelength residual emission from Venus measured with the NASA VLA.

III. PLANNED WORK FOR THE UPCOMING GRANT YEAR (JANUARY 1, 1998 - DECEMBER 31, 1998)

A. Interpretation of Venus Microwave Observations

Now that laboratory-based formalisms for the opacity of SO_2 (Suleiman et al., 1996) and gaseous H_2SO_4 (Kolodner and Steffes, 1997) under Venus atmospheric conditions have been derived, new interpretative studies of both Venus radio occultation absorptivity profiles and Venus microwave radio emission maps have begun. (See, e.g., Kolodner and Steffes, 1997, Appendix B, and Kolodner, 1997.) Already the results indicate a substantial latitudinal dependence of the abundance profiles of cloud-related gases consistent with a Hadley cell-type circulation. (See Figure 1.) Other investigators (Jenkins at SETI Institute/NASA-Ames Research Center and Butler at NRAO/VLA) have begun additional studies both of the VLA maps already made by our group and new maps at other wavelengths being made by Butler at NRAO. Additionally, Jenkins has recently completed reduction of 1994 Magellen radio occultation profiles, which when interpreted using our laboratory results, will give even more insight into the latitudinal variations of the abundances of sulfur-bearing gases in the Venus atmosphere.

In the next grant year, we will continue our interpretative studies of the Venus microwave radio emission maps and radio occultation studies, working with those other investigators, so as to yield the best possible understanding of the variations in constituent abundances and the atmospheric dynamics on a global basis. A paper describing these interpretive studies will be submitted to Icarus later this year.

B. Outer Planets Studies

In our most recent study of the microwave emission spectrum of Neptune (DeBoer and Steffes, 1996, reprint appended), we showed that in order to best match the most reliable disk-averaged emission measurements (1 mm to 20 cm), and not exceed the measurements of 13 cm and 3.6 cm absorptivity made by Voyager 2 at Neptune (Lindal, 1992), a Neptune atmosphere where the abundance of H_2S is greater than that of NH_3 below the putative NH_4SH cloud in the deep atmosphere is required. While such an atmosphere (e.g. 78% H_2, 19% He, 3% CH_4, plus 40 x solar H_2S and 0.2 x solar NH_3) gives an excellent fit to the microwave emission spectrum, its opacity is too low at 13 cm and 3.6 cm to explain the Voyager radio occultation results. It is possible, however, to match both emission spectra and the Voyager results by adding phosphine (PH_3) to the model.

Phosphine has been detected on Jupiter and Saturn at its strong rotational resonance (267 GHz, see Weisstein and Serabyn, 1994, 1996). Preliminary estimates with our Neptune model suggest that a PH_3 abundance between 10x and 20x solar best fits the microwave data. Note that Weisstein and Serabyn (1994a) inferred a 20x solar abundance at Saturn. Estimates of the microwave absorption spectrum from PH_3 have been made using the updated Poynter, Pickett, and Cohen line catalog (1994). While some line intensities have been measured, many, including the weak inversion lines in the centimeter wavelength range, have not; and no measurements of line shape parameters have been made. However, by assuming the Van Vleck-Weisskopf lineshapes and a range of broadening parameters, it is possible to set a range on the expected opacity.

In Figure 1 in DeBoer and Steffes (1996, reprint appended), we compare the opacity from an $H_2/He/H_2S$ mixture with that from an identical mixture which replaces H_2S with PH_3. This figure shows that the centimeter wavelength opacity from the mixture including PH_3 will exceed the opacity from the H_2S mixtures we successfully measured previously (DeBoer and Steffes, 1994). However, the actual opacity may vary by an order of magnitude depending on which lineshape parameters are used. Thus to accurately infer the PH_3 abundance in Neptune's atmosphere from centimeter-wavelength microwave data, accurate laboratory measurements of its opacity (and refractivity) are necessary.

In the next grant year, we will renovate the system used previously by DeBoer and Steffes (1994) to measure the opacity and refractivity of H_2S under simulated conditions for the outer planets, so as to measure the opacity and refractivity of PH_3. The renovations will include re-machining and re-plating the microwave resonators, as well as developing a PH_3 compatible gas handling system. The opacity and refractivity of the $H_2/He/PH_3$ mixture will be initially measured at 2.25 GHz (13.3 cm), 8.5 GHz (3.7 cm) and 21.7 GHz (1.38 cm) at pressures from 1 to 6 Bars and at three temperatures from 150K to 298K. In the future, the results will be used to develop a formalism for PH_3 opacity which will be used in the interpretation of radio occultation derived absorptivity profiles at Neptune and will provide PH_3 abundance estimates. The formalism will also be applied to our radiative transfer model, so as to derive accurate estimates of PH_3 abundance from Neptune microwave emission data.

IV. PROPOSED BUDGET

PRINCIPAL INVESTIGATOR: Paul G. Steffes (Georgia Institute of Technology)

TITLE: Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres

GRANT NUMBER: NAG5-4150
For the period of January 1, 1998 through December 31, 1998
(Third year of 3-year program, no carry-over from previous year)

ESTIMATED COST BREAKDOWN

I.	DIRECT SALARIES AND WAGES*:			$ 37,655
	A.	Principal Investigator (Paul G. Steffes) 17% time, calendar yar (.17 person-years)	$ 17,776	
	B.	1 Graduate Student (J. P. Hoffman) 50% time, calendar year (.5 person-years)	$ 16,848	
	C.	1 Senior Administrative Secretary 12% time, calendar year (.12 person-years)	$ 3,031	
II.	FRINGE BENEFITS**:	27.5% of Direct Salaries & Wages (less students)		$ 5,722
III.	MATERIALS, SUPPLIES, AND SERVICES			$ 1,500
	A.	Gases, liquids, and supplies (microwave connectors and o-rings) for Experiments	$ 900	
	B.	Miscellaneous Project Supplies (data storage media) and page charges	$ 600	
IV.	TRAVEL			$ 1,300
	A.	Travel for Student to AAS/DPS Meeting (Madison, WI, 5 days duration, airfare $600 plus registration and $ 100/day)		
		SUBTOTAL - ESTIMATE OF DIRECT COSTS:		$ 46,177
V.	OVERHEAD (Indirect Expense)**: 49% of Modified Total Direct Cost Base			$ 22,627
VI.	TUITION REMISSION ($799 per student per quarter)			$ 3,196
	TOTAL FIRST YEAR BUDGET REQUESTED FROM NASA:			$ 72,000

SUMMARY OF STAFFING REQUEST: SEE SECTION I (ABOVE)

* The salary and wage rates are based on FY98 salaries for the Georgia Institute of Technology. The Georgia Tech Fiscal Year is July 1 through June 30.
** Rates are for the period July 1, 1997 through June 30, 1998 and are subject to adjustment upon DCAA audit and ONR negotiations.

V. REFERENCES

DeBoer, D. R. and P. G. Steffes, 1996. Estimates of the tropospheric vertical structure of Neptune based or radiative transfer studies. Icarus 123, 324-335 (Reprint appended).

Hillman, J. J., D. A. Glenar, G. Bjoraker, N. J. Chanover, S. A. Severson, W. E. Blass, J. T. Bergstralh, 1996. "High spectral resolution imaging of Venus' night side using the GSFC near-IR AOTF camera". Bulletin of the American Astronomical Society 28, 1117.

Kolodner, M. A., 1997. Microwave Remote Sensing of Sulfuric Acid in the Venus Atmosphere, Ph.D.Dissertation, Georgia Institute of Technology, May 1997.

Kolodner, M. A., and P. G. Steffes 1996. The microwave absorption and abundance of sulfuric acid vapor in the Venus atmosphere. Bulletin of the American Astronomical Society, 28, 1116-1117. Presented at the 28th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Tucson, AZ, October 24, 1996.

Kolodner, M. A. and P. G. Steffes 1997. The microwave absorption and abundance of sulfuric acid vapor in the Venus atmosphere based on new laboratory measurements. Icarus, in press. (Preprint attached as Appendix B.)

Kolodner, M. A., S. H. Suleiman, B. J. Butler, and P. G. Steffes 1996. The abundance and distribution of sulfur-bearing compounds in the lower Venus atmosphere. EOS - Trans. AGU 77, Fall Meeting Supplement, F439. Presented at the Fall Meeting of the American Geophysical Union, San Francisco, CA, December 16, 1996.

Kolodner, M. A., S. H. Suleiman, B. J. Butler, and P. G. Steffes 1997. Latitudinal variations of sulfur compounds in the Venus atmosphere based on the correlation between VLA observations and radio occultation results. Bulletin of the American Astronomical Society 29, 1258. Presented at the 29th Annual Meeting of the division for Planetary Sciences of the American Astronomical Society, Cambridge, MA, August 1, 1997.

Poynter, R. L. , H. M. Pickett, and E. A. Cohen, 1994. Submillimeter, millimeter and microwave spectral line catalog. Available on-line via FTP from JPL. Described by Poynter, R. L. and H. M. Pickett, 1985 (same title), Applied Optics 24, 2235-2240.

Suleiman, S. H. 1997. Microwave effects of gaseous sulfur dioxide (SO_2) in the atmospheres of Venus and Earth. Ph.D. Dissertation, Georgia Institute of Technology, May 1997.

Suleiman, S. H., M. A. Kolodner, B. J. Butler, and P. G. Steffes, 1996. VLA Images of Venus at 1.3 cm and 2 cm wavelengths. Bulletin of the American Astronomical Society 28, 1117. Presented at the 28th Annual Meeting of the Division for Planetary Sciences of the American Astronomical Society, Tucson, AZ, October 24, 1996.

Suleiman, S. H., M. A. Kolodner, and P. G. Steffes, 1996. Laboratory measurement of the temperature dependence of gaseous sulfur dioxide (SO_2) microwave absorption with application to the Venus atmosphere. Journal of Geophysical Research (Planets) 101, 4623-4635.

Taylor, F. W., R. Beer, M. T. Chahine, D. J. Diner, L. S. Elson, R. D. Haskins, D. J. McCleese, J. V. Martonchik, and P. E. Reichley, 1980. Structure and meteorology of the middle atmosphere of Venus: Infrared remote sensing from the Pioneer Orbiter. Journal of Geophysical Research 85, 7963-8006.

Weisstein, E. W. and E. Serabyn 1994. Detection of the 267 GHz J=1-0 rotational transition of PH_3 in Saturn with a new fourier transform spectrometer. Icarus 109, 367-381.

Weisstein, E. W. and E. Serabyn 1996. Submillimeter line search in Jupiter and Saturn. Icarus 123, 23-36.

BIOGRAPHICAL SKETCH

PAUL G. STEFFES
PROFESSOR
SCHOOL OF ELECTRICAL AND COMPUTER ENGINEERING
GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332-0250

EDUCATION

S.B.	Electrical Engineering	1977
S.M.	Electrical Engineering	1977
	Massachusetts Institute of Technology	
Ph.D.	Electrical Engineering	1982
	Stanford University	

EMPLOYMENT HISTORY

Massachusetts Institute of Technology, Research Laboratory of Electronics, Radio Astronomy and Remote Sensing Group	
Graduate Research Assistant	1976-1977
Watkins-Johnson Company, Sensor Development, San Jose, California	
Member of the Technical Staff	1977-1982
Stanford University, Electronics Laboratory, Center for Radar Astronomy, Stanford, California	
Graduate Research Assistant	1979-1982
Georgia Institute of Technology, School of Electrical and Computer Engineering, Atlanta, Georgia	
Assistant Professor	1982-1988
Associate Professor	1988-1994
Professor	1994-Present

EXPERIENCE SUMMARY

At Massachusetts Institute of Technology

Responsible for development, operation, and data analysis for an 8-channel, 118 GHz radiometer system flown aboard the NASA Flying Laboratory (CV-990) as an engineering model for a meteorological sensing satellite. Duties included hardware development of millimeter-wave, microwave, analog, and A to D segments of the system, in addition to airborne operation and reduction of data. The research resulted in a Master's thesis entitled "Atmospheric Absorption at 118 GHz," detailing the first airborne measurement of high altitude atmospheric absorption in the 2.5 millimeter wavelength range, due to atmospheric oxygen.

At Watkins-Johnson Company

Responsibilities included proposals and system design and development, particularly in the area of millimeter-wave systems. Responsibility for millimeter-wave systems development included government sponsored study and development of ELINT (Electronic Intelligence) and radar warning receiving systems to frequencies as high as 110 GHz, as well as internal company sponsored development projects including a 60 GHz communications system and millimeter-wave downconverters.

At Stanford University

Research was concentrated in the area of microwave radio occultation experiments from Voyager and Mariner spacecraft, with specific interest in microwave absorption in planetary atmospheres. Work included computer-based theoretical development of microwave absorption coefficients for planetary atmospheres, to facilitate the use of radio occultation-derived microwave absorption profiles in determining constituent densities. Additional work included the development of a fully instrumented experimental facility for use in measuring the microwave properties of planetary atmospheres under simulated planetary conditions. The research resulted in a Ph.D. dissertation entitled "Abundances of Cloud-Related Gases in the Venus Atmosphere as Inferred from Observed Radio Opacity."

At Georgia Tech

Research Activities: Principal Investigator of the National Science Foundation Grant, "Remote Sensing of Clouds Bearing Acid Rain." This research studied and designed a microwave/millimeter-wave system for remotely sensing the pH of acidic clouds (1982-1983). Principal Investigator of the NASA Planetary Atmospheres Program, "Laboratory Evaluation and Application of Microwave Absorption Properties Under Simulated Conditions for Planetary Atmospheres." This research includes study of the interaction between atmospheric constituents and electromagnetic waves, along with application of these studies to spacecraft and radio telescopic measurements of the microwave absorption in atmospheres of Venus and the outer planets (1984-1998). Principal Investigator of the GTE Spacenet Program, "Satellite Interference Locating System (SILS)." The program involved location of uplink signals on the surface of the earth without disrupting regular satellite operations (1986-1990). Principal Investigator of the Emory University/Georgia Tech Biomedical Technology Research Center project, "Research in Development of a Non-Invasive Blood Glucose Monitoring Technique." This research involved the use of active infrared systems to determine glucose levels in the human eye and bloodstream (1988-1989), with subsequent support (1990-1991) from Lifescan, Inc. Principal Investigator of the NASA Pioneer Venus Guest Investigator Program, "Pioneer Venus Radio Occultation (ORO) Data Reduction: Profiles of 13 cm Absorptivity." This research inferred 13 cm wavelength absorptivity profiles using the Pioneer Venus Orbiter, and then used such profiles to characterize abundance profiles for gaseous H_2SO_4 in the Venus atmosphere (1988-1990). Principal Investigator/Team Member of NASA High Resolution Microwave Survey (HRMS). This research involved development and operation of the world's most sensitive receiving system used for a 1-10 GHz Sky Survey (1991-1994). Subsequent support has been provided by the SETI Institute (1994-1997). Developer of atmospheric radio occultation experiments conducted with the Magellan (Venus) Spacecraft (1991-1994). Director of the Ku Band Satellite Earth Station System. Responsible for development of a Ku-band uplink/downlink system for use in inter-university networks (1985-1995). Principal investigator in the NASA/ACTS Propagation Experiments Program (1994-1996). This research involves study of Ka-Band propagation effects.

Teaching Activities: Resource Professor for "Satellite Communications Systems" (graduate course). "Electromagnetics Applications" (undergraduate course covering Smith Charts, waveguides, and antennas), have also taught "Electromagnetics II (electrodynamics), "Signals and Systems," and "Survey of Remote Sensing."

Administrative Activities: Chairman, School of ECE Electromagnetics Technical Group, 1990-1996.

HONORS AND AWARDS

Member, Eta Kappa Nu.
Member, Sigma Xi.
Senior Member, IEEE (Member of 6 IEEE Societies).
Recipient of the Stewart Award (MIT for exceptional contribution to student extra-curricular life, 1977.
Recipient of the Metro Atlanta Young Engineer of the Year Award, presented by the Society of Professional Engineers, 1985.
Recipient of the Sigma Xi Young Faculty Research Award, 1988.
Associate Editor, Journa for Geophysical Research (JGR-Atmospheres), 1984-1989.
Appointed Member of the NASA Management and Operations Working Group for the Planetary Atmospheres Program (1986-1990).
Elected to the Electromagnetics Academy, October 1990.
Recipient of the Sigma Xi Best Faculty Paper Award, 1991.
Recipient of the NASA Group Achievement Award, "For outstanding contribution to the design, development, and operation of the High Resolution Microwave Survey Project, and its successful inauguration," March 1993.
Recipient of the 1996 IEEE Judith A. Resnik Award, "For contributions to an understanding of the Venus atmosphere through innovative microwave measurements," January 1996.

OTHER PROFESSIONAL AFFILIATIONS

Member, American Association for the Advancement of Science.

Member, American Astronomical Society, Division for Planetary Sciences.
Member, American Geophysical Union.
Member, American Institute of Physics.
Member, American Society for Engineering Education.
Elected Member, International Union of Radio Scientists (URSI), Commission J (Radio Astronomy).
Chairman, Atlanta Chapter, IEEE Antennas and Propagation Society and Microwave Theory and Techniques Society, 1986-1988. Director, IEEE Atlanta Section, 1988-1989.
Georgia Tech Chapter, Sigma Xi, Vice President, 1990-1991; President 1991-1992; Past-President, 1992-1993.
Chairman, Publicity Committee, 1993 IEEE International Microwave Symposium.

OTHER PROFESSIONAL ACTIVITIES

Proposal Reviewer for the NASA Planetary Astronomy Program, the NASA Planetary Atmospheres Program, the NASA Planetary Instrument Definition and Development Program, the NASA planetary Data Analysis Programs, the NASA Exobiology Program, and the NSF Communications Research Program.
Reviewer/Referee for Icarus (International Journal of Solar System Studies), Journal of Geophysical Research, Radioscience, IEEE Microwave and Guided Wave Letters, and for several textbooks in the area of electromagnetics.
Consultant to industry in the areas of microwave, millimeter-wave, and RF systems for communications, detection, and monitoring. This includes satellite communications, antenna systems, and propagation.
Expert witness in cases involving antenna/communications system performance, and the effects of environmental factors on such systems.

PATENTS

E. H. Orr and P. G. Steffes, "Method and System for Detecting Water Depth and Piloting Vessels," Patent # 4,757,481, issued July 12, 1988.

R. V. Tarr and P. G. Steffes, "Non-Invasive Blood Glucose Measurement System," Patent #5,243,983, issued September 14, 1993.

PUBLICATIONS

Theses

P. G. Steffes, "A Microwave (UHF) Television Repeater System," S.B. Thesis, Massachusetts Institute of Technology, 1976.

P. G. Steffes, "Atmospheric Absorption at 118 GHz," S.M. Thesis, Massachusetts Institute of Technology, 1977.

P. G. Steffes, "Abundances of Cloud-Related Gases in the Venus Atmosphere as Inferred from Observed Radio Opacity," Ph.D. Dissertation, Stanford University, 1982.

Journal Publications

P. G. Steffes and R. A. Meck, "Prototype Tests Secure Millimeter Communications," Microwave Systems News, vol. 10, pp. 59-68, October 1980.

V. R. Eshleman, D. 0. Muhleman, P. D. Nicholson, and P. G. Steffes, "Comment on Absorbing Regions in the Atmosphere of Venus as Measured by Radio Occultation," Icarus, vol. 44, pp. 793-803, December 1980.

P. G. Steffes and V. R. Eshleman, "Sulfur Dioxide and Other Cloud-Related Gases as the Source of the Microwave Opacity of the Middle Atmosphere of Venus," Icarus, vol. 46, pp. 127-13 1, April 1981.

P. G. Steffes and V. R. Eshleman, "Laboratory Measurements of the Microwave Opacity of Sulfur Dioxide and Other Cloud-Related Gases Under Simulated Conditions for the Middle Atmosphere of Venus," Icarus, vol. 48, pp. 181-187, November 1981.

P. G. Steffes and V. R. Eshleman, "Sulfuric Acid Vapor and Other Cloud-Related Gases in the Venus Atmosphere: Abundances Inferred from Observed Radio Opacity," Icarus, vol. 51, pp. 322-333, August 1982.

P. G. Steffes, "Millimeter-Wavelength Remote Sensing of Stratospheric Sulfur Dioxide," EOS, vol. 64, pp. 198-199, May 1983.

P. G. Steffes, "Laboratory Measurements of the Microwave Opacity and Vapor Pressure of Sulfuric Acid Under Simulated Conditions for the Middle Atmosphere of Venus," Icarus, vol. 64, pp. 576-585, December 1985.

P. G. Steffes, "Evaluation of the Microwave Spectrum of Venus in the 1.2 to 22 cm Wavelength Range Based on Laboratory Measurements of Constituent Gas Opacities," Astrophysical Journal, vol. 310, pp. 482-489, November 1, 1986.

P. G. Steffes and J. M. Jenkins, "Laboratory Measurements of the Microwave Opacity of Gaseous Ammonia (NH3) Under Simulated Conditions for the Jovian Atmosphere," Icarus, vol. 52, pp. 35-47, October 1987.

J. M. Jenkins and P. G. Steffes, "Constraints on the Microwave Opacity of Gaseous Methane and Water Vapor in the Jovian Atmosphere," Icarus, vol. 76, December 1988.

J. Joiner, P. G. Steffes, and J. M. Jenkins, "Laboratory Measurements of the 7.5-9.38 mm Absorption of Gaseous Ammonia (NH3) Under Simulated Jovian Conditions," Icarus, vol. 81, pp. 386-395, 1989.

W. W. Smith and P. G. Steffes, 'Time Delay Techniques for a Satellite Interference Location System," IEEE Transactions on Aerospace and Electronic Systems, vol. 25, pp. 224-231, March 1989.

P. G. Steffes, M. J. Klein, and J. M. Jenkins, "Observation of the Microwave Emission of Venus from 1.3 to 3.6 cm," Icarus, vol. 84, pp. 83-92, March 1990.

J. M. Jenkins and P. G. Steffes, "Results for 13 cm Absorptivity and H2SO4 Abundance Profiles from the Season 10 (1986) Pioneer-Venus Orbiter Radio Occultation Experiment," Icarus, vol. 90, pp. 129-138, March 1991.

W. W. Smith, Jr. and P. G. Steffes, "A Satellite Interference Location System Using Differential Time and Phase Measurement Techniques," IEEE Aerospace and Electronic Systems Magazine, vol. 6, pp. 3-7, March 1991.

A. K. Fahd and P. G. Steffes, "Laboratory Measurement of the Millimeter-Wave Properties of Liquid Sulfuric Acid (H2SO4)," Journal of Geophysical Research (Planets), vol. 96, pp. 17,471-17,476, September 25, 1991.

J. Joiner and P. G. Steffes, "Modeling of the Millimeter-Wave Emission of Jupiter Utilizing Laboratory Measurements of Ammonia (NH3) Opacity," Journal of Geophysical Research (Planets), vol. 96, pp. 17,463-17,470, September 25, 1991.

P. G. Steffes and G. P. Rodrigue, "Comment on Rapid Pulsed Microwave Propagation," IEEE Microwave and Guided Wave Letters, vol. 2, pp. 200,201, May 1992.

A. K. Fahd and P. G. Steffes, "Laboratory Measurements of the Microwave and Millimeter-Wave Opacity of Gaseous Sulfur Dioxide (SO2) under Simulated Conditions for the Venus Atmosphere," Icarus, vol. 97, pp. 200-210, June 1992.

A.J. Gasiewski and P.G. Steffes, "University Profile: The Laboratory for Radioscience and Remote Sensing at the Georgia Institute of Technology, IEEE Geoscience and Remote Sensing Society Newsletter, vol. 88, pp. 16-21, September 1993.

J. Joiner, P. G. Steffes, and K. S. Noll, "Search for Sulfur (H2S) on Jupiter at Millimeter Wavelengths," IEEE Transactions on Microwave Theory and Techniques, vol. 40, pp. 1101-1109, June 1992.

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AUGUST 1997

The Microwave Absorption and Abundance of Sulfuric Acid Vapor in the Venus Atmosphere

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New abundance profiles of gaseous sulfuric acid (H_2SO_4) vapor have been computed based on the measured absorptivity profiles of the Venus atmosphere obtained during the October 1991 and December 1992 Magellan radio occultation experiments (Jenkins *et al.*, *Icarus* 110, p. 79, 1994 & Hinson and Jenkins, *BAAS* 27, p. 1079, 1995). These abundance profiles are different than those previously reported by Jenkins *et al.* (1994) due to the completion of new laboratory measurements of the microwave opacity of gaseous H_2SO_4 in a CO_2 environment. While these new experiments follow the same general procedure as Steffes (*Icarus* 64, p. 576, 1985 & *Astrophys. J.* 310, p. 482, 1986), a more accurate determination of the H_2SO_4 to CO_2 number mixing ratio is achieved by using resonators with gold as opposed to silver-plating to eliminate unaccounted for chemical reactions. In addition, a significant reduction in the uncertainty of the absorptivities is achieved due to our ability to account for changes in the dielectric properties of the resonators when a lossy gaseous mixture is introduced into them. New multiplicative expressions for the microwave opaicty of gaseous H_2SO_4 in a CO_2 environment are presented. These expressions yield abundances of sub-cloud gaseous H_2SO_4 in the Venus atmosphere on the order of 1 to 3 ppm. This new formalism, together with a Ben-Reuven line shape model for the microwave opacity of gaseous SO_2 in a CO_2 environment developed by Suleiman *et al.* (*JGR Planets* 101, p. 4623, 1996), is being incorporated into a radiative transfer model to compute variations of gaseous H_2SO_4 and SO_2 across the disk of the planet from microwave brightness maps of Venus obtained using the Very Large Array.

This work was supported by the NASA Planetary Atmospheres Program under grant NAGW-533.

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VLA Images of Venus at 1.3 cm and 2 cm Wavelengths

S. H. Suleiman, M. A. Kolodner (Georgia Inst. of Tech.), B. J. Butler (NRAO), P. G. Steffes (Georgia Inst. of Tech.)

On April 5, 1996, we performed an observation of Venus using the Very Large Array (VLA) at 15 GHz (2 cm) and 22 GHz (1.3 cm) simultaneously. High resolution continuum images for Venus were obtained at both frequencies. These images show significant polar darkening at latitudes above 60° which is consistent with the results obtained by the Pioneer Venus Orbiter Infrared Radiometer (OIR) experiment (Taylor *et al.*, *J. Geophys. Res.* 85, 7963-8006, 1980). These images are currently being used to detect potential spatial (longitudinal and latitudinal) variations in the abundances of gaseous sulfur dioxide (SO_2) and gaseous sulfuric acid (H_2SO_4) across the disk of Venus. Our new radiative transfer model (RTM) has shown that the emission spectrum is especially sensitive to the abundances of these constituents at these wavelengths. The detection of these constituents is being accomplished by matching the computed emission from our RTM to the measured emission of Venus by the VLA. Our RTM incorporates the newly developed Ben Reuven formalism which provides a more accurate characterization of the microwave absorption of gaseous SO_2 (Suleiman *et al.*, *J. Geophys. Res.* 101, 4623-4635, 1996). A description of the observation, visibility data, and images are presented.

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The Abundance and Distribution of Sulfur-Bearing Compounds in the Lower Venus Atmosphere

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Microwave remote sensing of Venus from earth-based radio observatories and in-situ orbiters have yielded a wealth of data for interpretation and analysis on the composition of the lower Venus atmosphere. On April 5, 1996, we performed a dual frequency microwave observation of Venus using the Very Large Array (Suleiman et al., *BAAS* **28**, 1996). High resolution maps obtained at both 15 GHz (2 cm) and 22 GHz (1.3 cm) displayed little variation in the brightness temperature across the disk of the planet in the equatorial zones and mid-latitude regions, but showed significant darkening (>20 Kelvins) in the polar regions at latitudes above 60°. Our newly developed radiative transfer model (RTM), used to interpret the brightness maps, has shown particular sensitivity to the microwave opacity of gaseous sulfur dioxide (SO_2) and gaseous sulfuric acid (H_2SO_4) in the lower Venus atmosphere at K-band (22 GHz) and KU-band (15 GHz) respectively. Our RTM incorporates a newly developed Ben Reuven formalism for the microwave absorption of gaseous SO_2 (Suleiman et al., *J. Geophys Res.* **101**, p. 4623, 1996) and newly developed multiplicative expressions for the microwave absorption of H_2SO_4 vapor based on new laboratory data (Kolodner and Steffes, *BAAS* **28**, 1996). Our analysis of the brightness maps show little gaseous SO_2 (<100 ppm) and very little H_2SO_4 vapor in the equatorial and mid-latitude regions, but yield larger abundances of gaseous SO_2 (>100 ppm) and H_2SO_4 vapor (>3 ppm) in the polar regions. Significant opacity in the polar zones was also observed from the measured absorptivity profiles of the Venus atmosphere obtained during the October 1991 and December 1992 Magellan radio occultation experiements (Jenkins et al., *Icarus* **110**, p. 79, 1994 & Hinson and Jenkins, *BAAS* **27**, p. 1079, 1995). These absorptivity profiles are inverted to yield specific abundance profiles of these sulfur-bearing compounds.

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Latitudinal Variations of Sulfur Compounds in the Venus Atmosphere Based on the Correlation Between VLA Observations and Radio Occultation Results

M.A. Kolodner, S.H. Suleiman (Georgia Inst. of Tech.), B.J. Butler (NRAO), P.G. Steffes (Georgia Inst. of Tech.)

To identify the presence of potential spatial variations in the distributions of sulfur compounds (H_2SO_4(g) and SO_2) across the disk of Venus, a dual-frequency radio observation was performed with the NRAO/VLA at 14.94 GHz (2 cm) and 22.46 GHz (1.3 cm) on April 5, 1996. The resulting brightness maps have been compared with a radiative transfer model, which shows both equatorial and polar limb darkening beyond that due to a simple CO_2/N_2 atmosphere. Our radiative tranfer model shows that the measured darkening results directly from the microwave opacity of SO_2 and H_2SO_4(g).

Specifically, in the equatorial regions, it has been found that the limb darkening corresponds to that expected from an H_2SO_4(g) abundance profile such as that derived from the equatorial Mariner 10 radio occultation experiment, and from a nominal subcloud SO_2 abundance of 75 ppm. In the polar regions, the increased limb darkening is consistent with the more broad vertical distribution of gaseous H_2SO_4 such as that derived from Magellan radio occultation experiments in high latitude regions. The magnitude of the polar limb darkening also requires a corresponding elevation in the sub-cloud SO_2 abundance to 150 ppm or more.

This work was supported by the NASA Planetary Atmospheres Program under grants NAG5-4190 and NAGW-533.

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